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V I P E R: SYSTEMS INTEGRATION STATUS

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NASA's Artemis Program plans to return humans to the Moon for an extended stay. To do so will require substantial resources to sustain that continued human presence, including continuous supplies delivered from the Earth. Given the expense and complexity of resource deliveries from Earth, if some resources were indigenously available, substantial logistical savings could be available by "living off the land", wherever possible.

The LCROSS^[1], LRO and other missions have confirmed the presence of resources such as water-ice and other volatiles in lunar polar regions, so the next step is to understand the scientific nature and physical distribution of those candidate resources. Those local volatiles could be processed into propellants and human life-supporting needs, reducing risk of maintaining a permanent human presence on the Moon.

The Volatiles Investigating Polar Exploration Resource (VIPER) is a surface mobility scientific platform, designed to spend ~100 days mapping and surveying four different Ice Stability Regions to understand the scientific nature and distribution of water and other volatiles. VIPER will also provide scientific mineralogical context of the lunar regolith, such as the presence of silicon and light metals in lunar regolith, providing a composite picture of resource availability and sustainment.

This paper will discuss the latest systems-level integration activities by the VIPER team, following our initial introduction to this mission at IAC2021^[2]. The VIPER team successfully passed its Systems Integration Review (SIR) in late-2022, and in early 2023, began system-level surface segment (rover) flight hardware assembly.

VIPER is managed within NASA's Science Mission Directorate (SMD), utilizing the Commercial Lunar Payload Services (CLPS) lunar delivery model with partner, Astrobotic, Inc.

I. MISSION OVERVIEW

The VIPER Mission is focused on supporting long-term stays on the Moon, including understanding the nature and concentration of water and other volatiles. VIPER intends to study both the processes that formed/enable volatiles, as well as understanding their distribution. VIPER will inform future missions planning, both state-sponsored and commercial, in moving towards harvesting and processing those resources. These goals will ultimately result in the creation of lunar resource maps, enabling assessments of the ore grade of lunar polar volatiles. Understanding the ore grade will help determine the economic suitability of using these resources for human sustainment and fuel, as discussed in an earlier IAC paper on the VIPER mission^[2]. VIPER represents the next step forward for lunar polar missions, beginning with resource identification, then In Situ Resource Utilization (ISRU), and finally mining, bulk production, and storage.

The VIPER team has established four different regions in the lunar polar landscape, each defined by

their predicted thermal stability of ice. These regions are called Ice Stability Regions, or ISR's, which range from surface regions, down to 1m below the surface.

The VIPER science and surface planning teams have been working rover surface plans since mission inception, and even earlier, building on the pathfinding work of the NASA-ARC Resource Prospector (RP) mission^[3] design construct. In 2022 the surface planning focus became more complex as we added-in landing site planning, with VIPER's CLPS partner, Astrobotic, to assure VIPER needs were met in conjunction with Griffin lander and GM-1 mission capabilities. This work continues to this day, as we prepare for both primary and contingent launch dates.

The VIPER team is using their suite of custom Artificial Intelligence (AI) planning tools developed at NASA-Ames Research Center in California. These tools help plan visits to multiple ISR's, characterizing their nature. Armed with VIPER's data, broader conclusions can be made, across the entire lunar polar landscape, as it relates to polar-region volatiles.

II. VIPER SUBSYSTEM ASSEMBLY

When flight teams enter NASA's "Phase D", it indicates the mission design is complete and now the focus turns to subsystem level acquisitions and manufacturing needs. These manufactured piece-parts and assemblies, which will become the Subsystems of the roving platform, for VIPER. Of course, some acquired items will have started long before entering into Phase D, due to the sometimes-lengthy procurement lead times to get these items, *which has only gotten more challenging for missions operating through a global pandemic and resultant global supply chain shortages*.

Example subsystems would be the rover structure/chassis, or the thermal management system, or the communications systems [Fig. 1], or even the assembly of the wheels [Fig. 2]. Each of these



Fig. 1: Assembly of the VIPER communications mast (flight and engineering units)

subsystems has teams assigned to them to carry the design forward into physical manifestation. These teams are made up of a combination of the original subsystem designers, coupled with a new cadre of individuals who carry specific skills associated with



Fig. 2: Assembly of the VIPER rover wheels

system assembly and test.

Early in this phase, the team begins practicing how the rover will practically be assembled. The overall VIPER system was designed with a certain assembly approach in mind, but there is nothing like attempting to build the system, in order to reveal the effectiveness of the original design. Further, it is much better to be discovering any deficiencies in design approach on something other than the flight hardware, in case problem areas are encountered.

For this reason, the VIPER team took an "Assembly pathfinder" approach. The assembly pathfinder allowed the team to learn and practice building the system before the assembly of the actual rover system. This approach included printing 3D

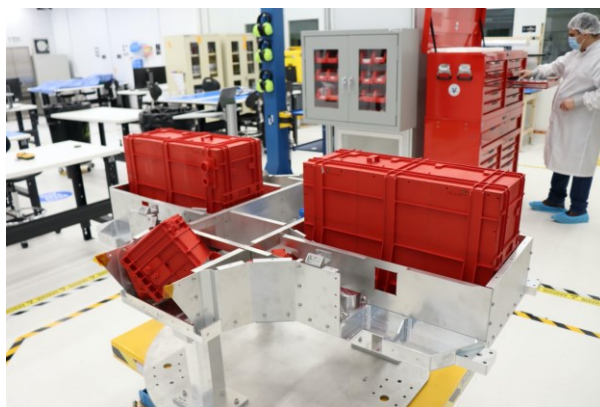


Fig. 3: 3D-printed models of various VIPER internal subsystems in mock-up rover chassis

models of the pertinent hardware, to safely manipulate and learn how this hardware will be assembled [Fig. 3]. It enables practicing approaches and writing procedures based on that learning. In fact some of the trickier pieces of hardware could not be installed the way they were originally envisioned, so new Mechanical Ground Support Equipment (MGSE) had to be developed to compensate for this – all before ever touching real flight hardware.

III. VIPER SUBSYSTEM TEST

While the process of subsystem assembly would theoretically occur before beginning testing on subsystems, the reality is that this phase is fraught with schedule challenges, whether due to late-arriving hardware from vendors, or missteps during the build process, or any number of other issues that will force alteration of your plans. For this reason, it is important to always be looking for activities that can be started earlier, as a contingency; this includes beginning subsystem level testing in some areas, even while not

yet having all the hardware complete in other areas. It is a challenging, but necessary way to operate against a fixed schedule framework.

For example, the VIPER team moved into initial testing with some of its electronic systems, as soon as possible. A typical way to do this is to electrically connect various engineering unit versions of the flight hardware into a “FlatSat” [Fig. 4]. A FlatSat is a temporary assembly of key electrical components on a table (a “flattened satellite”), connected as they would be with the actual flight system. The value of the FlatSat is to confirm hardware inter-functionality between components, but with additional benefits:

- Getting the team familiar with the hardware

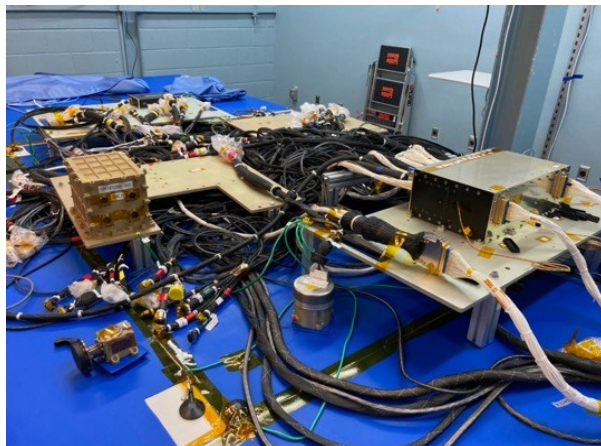


Fig. 4: FlatSat of VIPER engineering unit electronic components

- Confirming initial cable harnessing needs and functionality (channelization)
- Confirming hardware is performing as expected
- Confirming software driver interfaces
- Providing a testbed for testing scenarios

This VIPER FlatSat construct can even be abstracted to the VIPER-Griffin lander system, which was our next step - assuring the VIPER avionics and Griffin lander avionics are compatible. From launch, through lunar transit, to landing, the VIPER rover is sitting atop the Griffin Lander, communicating commands and telemetry through the Griffin avionics. VIPER needs to assure this compatibility early, so any issues could be addressed early. The VIPER and Griffin teams created avionics simulator on laptops, representing each the rover and lander avionics, connecting the two via the communications protocols



Fig. 5: Rover-lander interface testing

that will be used on mission, to verify intersystem compatibility [Fig. 5]

To extend this idea further, there is also whole launch stack testing that occurs during this time – in this case in the mechanical domain. This testing attempts to assure that the lander and VIPER rover will survive the harsh environment of launch loads. To accomplish this, a structural representation of the VIPER rover, the Griffin lander, and the payload adaptor fitting (PAF) from the launch vehicle, are assembled as they will be during the actual flight (the launch stack). These test articles are called Structural Test Models (STMs), and the purpose of this test is to assure structural and modal compatibility between each of these key components, that are being developed on their own. The earlier design phase of course intended to assure that compatibility, but only after testing these STMs in a launch stack configuration, on a vibration table, will the teams be sure about compatibility of the stacked system during launch.

VIPER subsystem performance testing also occurs during this phase, and sometimes even earlier to support needed early procurements for the flight hardware. One example is VIPER’s wheel design. While rover wheels have been designed in the past, the environments and soil characteristics for a lunar south pole mission are different than Mars missions; further,



Fig. 6: VIPER 40km wheel endurance testing over lunar soil simulant and rocks

the VIPER rover moves in a very different way that earlier NASA rover designs, so it is critical that the VIPER team fully understand the capability (and limitations) of its design.

An example of this is VIPER wheel endurance testing [Fig. 6]. We tested the design of the VIPER rover wheel to failure, to understand the design weaknesses and needed performance of this critical subsystem – testing well beyond the design intent for the mission lifetime. A 40km test revealed more than sufficient rover wheel life for the VIPER mission.

IV. VIPER SYSTEM TESTING

While the subsystem testing is occurring, whole system test is also occurring to both verify design intent, but also to test algorithms and SW estimators. VIPER's ability to successfully navigate across the lunar surface is based not just on VIPER's ability to see its environment, but to estimate what might not be

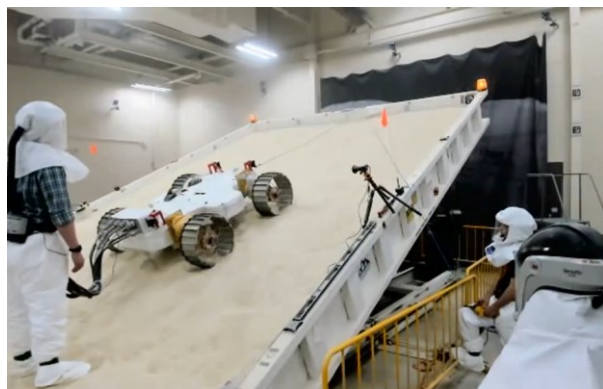


Fig. 7: VIPER slip testing at the NASA-GRC SLOPE facility

apparent from the instruments, for example slippage in the soil [Fig. 7].

For this reason, VIPER has developed algorithms to make estimates of what is happening to the rover on the surface, based on the measurements *it can make* with its various instruments and cameras. This is a tedious and detailed process and so this work must be occurring far before launch to fold those algorithms into the rover flight software design.

VIPER is also performing system testing of the Rover's tracking abilities in relevant environments. When a rover moves across an uneven surface but needs to be able to track a communications ground station on Earth, it is critical that the rover's attitude be able to hold lock on a spatial point, even while the rover is navigating rocks and craters at the wheels. To

verify this capability, evening testing was conducted with the engineering unit rover navigating over nominal surface defects, while checking the system's ability to hold lock with the star tracker (using the Moon), within an allowable error band [Fig. 8]. This

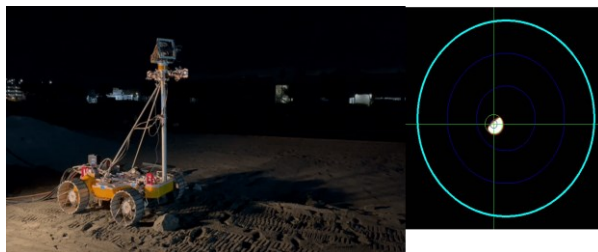


Fig. 8: VIPER navigating a sink tank to test alternative locomotion means

system has been tuned to maximize the performance for the VIPER team's environmental expectations.

VIPER is also studying alternative gates of movement, should it find itself embedded in the expected super-soft soils in permanently shadowed regions (PSRs). The VIPER team is making use of rover sink tanks at NASA, which are filled with perfectly spherical beads, that pass by each other with ease, providing virtually no structural buoyancy for test articles placed on the surface – including rovers [Fig. 9]. While the VIPER team does not expect lunar soil to behave this way, given the known, very sharp nature of lunar regolith grains, the LCROSS mission also discovered that the soil could be very lightly packed in permanently shadowed regions, so sinkage is a realistic threat. The VIPER team is therefore conducting multiple roving tests in the sink tanks over the past couple years, coming to understand the wheel-soil interactions and optimizing best ways to navigate out



Fig. 9: VIPER navigating a sink tank to test alternative locomotion means

of such conditions, including alternate locomotion means.

Finally, the VIPER and Astrobotic teams have conducted a series of two test campaigns to test the

tricky operation of rover egress from the lander down “rampways”. These tests have taken place at NASA-GRC and NASA-ARC [Fig. 10] so far, and study all aspects of rover egress, from points of potential physical interference, to situational awareness and



Fig. 10: VIPER navigating a sink tank to test alternative locomotion means

training for the rover drivers, to traction needs between the rover and rampways. The rover driver training experience has been especially useful, as they are sequestered in a different room, with only rover and lander imagery to guide their driving (as it will be on the Moon).

These tests have proven to be tremendously useful in optimizing the lander’s rampway design. Most recent discoveries revealed the need for fiducial markings on the rampways, which could provide additional, helpful situational awareness for the rover drivers. These egress tests also revealed rover-lander interferences that were not immediately apparent in the CAD design files, merged between the rover and lander. As with all testing, there’s nothing better than watching actual interactions of separately developed hardware, to retire risk.

V. VIPER FACILITIES PREPARATION

There is also an adjacent preparatory activity, critical for any flight project, and that is getting the needed test facilities readied for verifying rover readiness for the mission. Equally important is the readying of the team to perform tests in these sometimes large and complex facilities.

Since handling spaceflight hardware is always a risk and needing to be protected from human risk exposure, the VIPER team has been practicing the logistics of conducting these sometimes-large-scale tests, including the activity of transporting hardware between facilities. For these early tests VIPER is making use of the rover STM, both because the flight hardware is not yet ready, but also because we want to protect that flight hardware from harm while we’re

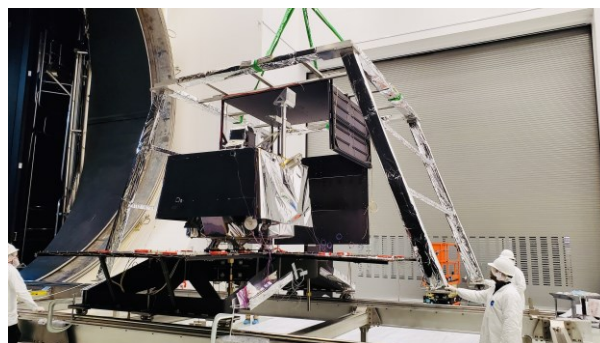


Fig. 11: VIPER Structural Test Model in a thermal radiant heat enclosure, sitting atop a cart that enables rolling the whole test assembly into the large TVAC chamber

defining test procedures and practicing logistics [Fig. 11].

While all these hardware-focused activities are occurring with the rover, it is important to remember there is a parallel track activity happening with Mission Systems (Ops or MS). It is no small activity getting an operational system laid out, configured, and verified with all the network security and connectivity in place in advance of the mission. Further, this system is not only needed in time to support the launch date, but more than a year in advance of that for the operational



Fig. 12: VIPER Simulation test #3 at the NASA-ARC Multi-Mission Operations Center (MMOC)

team to begin simulations, engineering readiness tests and operational readiness tests [Fig. 12]. In the case of complex surface operations missions like VIPER, there are multiple rooms for the Mission Operations Center, Science Operations Center, Payload Operations Center, and various backrooms at NASA-ARC, NASA-JSC, and vendors, to provide technical support during the VIPER mission.

VI. VIPER SYSTEM ASSEMBLY

As the various subsystems are getting assembled and verified, the overall mission schedule demands that system-level rover assembly begin, even before all the subsystems may be ready. This is due to a rover being a nested assembly by its nature, with a very particular order in which assembly can occur. This is very different, for example, than an axially-designed impactor mission, like LCROSS^[1], where the technicians can move around the vehicle working on various subsystems whenever convenient.

It's not hard to imagine that rover assembly begins with the lower chassis, not unlike the build of an automobile [Fig. 13]. The chassis is the structural core

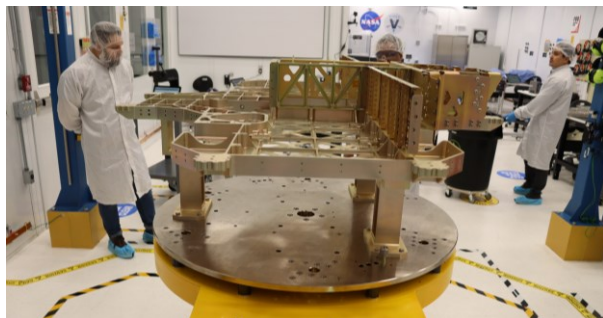


Fig. 13: Early VIPER flight chassis assembly

of the rover, with all assemblies relying on this central piece of hardware.

The lower frame assembly fit-up is next, but only because it is available to check-out [Fig. 14]. It will not be permanently installed yet because there are many more subsystems and pieces of hardware needed to be installed in the lower chassis, before occluding access with that lower frame. After fit-checking, this frame is set-aside awaiting a later installation. *This is all part of the realities of pandemic late-arriving hardware... The VIPER team has had to adapt to conditions live, making opportunities of the time we have while waiting on other hardware to arrive.*

This is the progress so far at the writing of this paper. System-level assembly continues into the fall of 2023, followed by moving into the system-level testing



Fig. 14: Early VIPER flight chassis assembly

phase that continues into 2024, before handover to Astrobotic for launch stack assembly, prior to launch.

VII. PROGRAM STATUS

In the Fall of 2022, VIPER successfully passed its Systems Integration Review (SIR), which means the Agency approved it proceeding into full systems-level integration of the flight unit, as described earlier in this paper. The VIPER team is proceeding towards a late-2024 mission start on the lunar surface in the Mons Mouton region of the South Pole.

The VIPER team has been challenged by *many* late vendors delivering their critical hardware to the VIPER team. The pandemic, and the ensuing global supply chain, has impacted everything from the most complex flight hardware to the availability of simple solvents. Some VIPER vendors are also under financial stress, requiring some very careful planning and close dialogue with the leadership of these companies.

This supply-chain reality has forced VIPER into a continuous state of adaptation, planning and replanning around breaking news about hardware late deliveries. The VIPER team has had to navigate more than half a dozen key rover deliverables being between 12-18 months late, with some hardware still outstanding as of the writing of this paper.

To compensate for these very late arriving hardware elements, VIPER leadership has had to parallelize work. In doing so, more staff has been required to complete the originally work, in less time.

VIPER has also developed clever ways to satisfy multiple test needs, with single tests, to further save the

time required to conduct originally planned sequential tests. Some of this testing can satisfy both system verification needs as well as mission operations needs.

VIII. SUMMARY

Since 1994, several lunar exploration missions have indicated the presence of volatiles, specifically hydrogen, in potentially large quantities in permanently shadowed regions at the lunar poles. Lunar missions from Clementine and Lunar Prospector to LCROSS¹ and LRO have confirmed the presence of volatiles at the lunar poles in permanently shadowed regions (PSRs). Now it is time for a mission to go into these volatiles areas of interest and confirm the makeup and composition of volatiles to inform follow-on missions.

Follow-on missions will perform technology demonstrators, performing early-ISRU demonstrations, that will later be scaled for harvesting these important resources in bulk.

The VIPER mission has officially entered the flight integration phase, which will continue throughout 2023. The VIPER team is also looking forward to 2024 by practicing both rover-lander egress activities, as well as rehearsing the logistics required to support flight vehicle testing in early-2024, prior to handover to the VIPER lander partner, and begin launch vehicle integration.

All images courtesy of NASA.

¹Andrews, D. R., “LCROSS – Lunar Impactor: Pioneering Risk-Tolerant Exploration in a Search for Water on the Moon,” 7th International Planetary Probe Workshop (IPPW-7), Barcelona, Paper IAC-11-A5.1.4, 2011.

²Andrews, D. R., “VIPER: Introduction to the Resource Prospecting Mission” 72nd International Astronautical Congress (IAC-21), Dubai, UAE, Paper IAC-21,A3,2A.4,x63298, October, 2021.

³Andrews, D. R., “Resource Prospector (RP): Pathfinding In-Situ Resource Utilizations,” 14th Reinventing Space Conference, London, UK, Paper BI-RS-2016-31, 2016.